THE DENSITY PROFILE OF MASSIVE GALAXY CLUSTERS FROM WEAK LENSING

H. DAHLE
Institute of Theoretical Astrophysics, University of Oslo,
P.O. Box 1029, Blindern, N-0315 Oslo, Norway

We use measurements of weak gravitational shear around a sample of massive galaxy clusters at $z = 0.3$ to constrain their average radial density profile. Our results are consistent with the density profiles of CDM halos in numerical simulations and inconsistent with simple models of self-interacting dark matter. Unlike some other recent studies, we are not probing the scales where the baryonic mass component becomes dynamically important, and so our results should be directly comparable to CDM N-body simulations.

1 Introduction

While the concordance flat ΛCDM model, in which the matter density is dominated by cold dark matter (CDM), provides a good fit to observed large scale-properties of the universe, there remain some possible small-scale problems for this model.

Numerical simulations of structure formation in a CDM model predict that the dark matter (DM) halos of $L_\star$ galaxies such as the Milky Way should contain a number of subhalos that exceed the observed number of satellite dwarf galaxies by 1-2 orders of magnitude (e.g. Klypin et al. 1999; Moore et al. 1999a). Strongly suppressed star formation in the subhalos could be a possible solution to this problem. Observations of anomalous flux ratios of strongly gravitationally lensed multiple quasar images (Kochanek & Dalal 2003) and observations of the dynamics of optically dark high-velocity gas clouds in the local group (Robishaw, Simon & Blitz 2002) appear to be qualitatively consistent with this proposed solution.

In addition, the simulations predict that DM halos have cuspy inner density profiles $\rho(r) \propto r^{-\alpha}$, with α somewhere in the range between 1.0 (Navarro, Frenk & White 1997; hereafter NFW) and 1.5 (Moore et al. 1999b). This appears to contradict the observed dynamics of DM-dominated low surface brightness galaxies which favour softer cores with $\alpha = 0.2 \pm 0.2$ (de Blok, Bosma, & McGaugh 2003). On the scales of galaxy clusters, some studies indicate shallower

density profiles than those predicted from CDM simulations (Sand et al. 2003), while others give α values that are consistent with CDM predictions (Bautz & Arabadjis 2003).

Attempts have been made to solve these small-scale problems of CDM by proposing DM models that modify its behavior on small scales. Some examples of these are models in which the DM is self-interacting (Spergel & Steinhardt 2000), self-annihilating (Kaplinghat, Knox & Turner 2000), fluid (Peebles 2000; Arbey, Lesgourgues & Salati 2003), warm (e.g., Sommer-Larsen & Dolgov 2001), repulsive (Goodman 2000), fuzzy (Hu, Barkana & Gruzinov 2000), decaying (Cen 2001), is both self-interacting and warm (Hannestad & Scherrer 2000), acts as mirror matter (Mohapatra, Nussinov & Teplitz 2002) or has its gravitational interaction with baryonic matter suppressed on small scales (Piazza & Marioni 2003). Of these, the self-interacting DM model of Spergel & Steinhardt is the one which has been explored in most detail. Here, we put limits on this model by using weak gravitational lensing to measure the average density profile of an ensemble of massive galaxy clusters. Details of this work are given by Dahle, Hannestad & Sommer-Larsen (2003).

2 Constraints on the DM halo profile

Our data set is a subset of the weak gravitational lensing measurements of 38 X-ray luminous clusters presented by Dahle et al. (2002). This subset consists of 6 clusters at $z = 0.3$ for which weak gravitational shear has been measured out to a projected radius of 3 h_{65}^{-1} Mpc. We fit the average observed radial shear profile to a "generalized NFW profile" on the form

$$\rho(r) = \frac{\delta_c \rho_c}{(r/r_s)^{\alpha}(1+(r/r_s))^{3-\alpha}}. \tag{1}$$

For the model above, the characteristic density δ_c is

$$\delta_c = \frac{200}{3}\left[\int_0^1 x^2 (cx)^{-\alpha}(1+cx)^{\alpha-3} dx\right]^{-1}. \tag{2}$$

This model has a concentration parameter c defined by $c = r_{200}/r_s$, where $\overline{\rho}(r_{200}) = 200\rho_{\rm c}$ and $\rho_{\rm c}$ is the critical density. The outer slope at $r >> r_s$, $\rho \propto r^{-3}$, is chosen to be the same as the outer slope of simulated CDM halos, while the inner slope α is a free parameter. The result of our fit is given in Figure 1 which shows joint confidence limits for α and $c_{\rm vir}$ (defined as $c_{\rm vir} = r_{\rm vir}/r_s$, where $r_{\rm vir}$ is the virial radius of the halo). The CDM simulations predict a $(z+1)^{-1}$ redshift-dependence and significant intrinsic scatter in the values of $c_{\rm vir}$ (Jing 2000; Bullock et al. 2001). A prediction for the value and scatter of $c_{\rm vir}$ for massive ($M_{\rm vir} = 2 \times 10^{15} M_{\odot}$) clusters in a ΛCDM universe is indicated in Figure 1.

Our data constrain α to be in the range $0.9 < \alpha < 1.6$ (68% CL), and $\alpha < 0.5$ is excluded at the 95% level. We also find that the data are consistent with an isothermal sphere with a finite core, $\rho(r) \propto (r^2 + r_c^2)^{-1}$, where r_c is the core radius. For the case of self-interacting dark matter, our constraints on the core radius implies a self-interaction cross section $\sigma_\star \leq 0.1 {\rm cm}^2{\rm g}^{-1}$ (c.f. Yoshida et al. 2000, Meneghetti et al. 2001). This is at least an order of magnitude smaller than the cross section required to explain the observed rotation curves of low surface brightness galaxies (Davé et al. 2001).

3 Comparison with other results

Different recent studies give a wide range of values for α. Sand et al. (2003; see also Sand, these proceedings) use a combination of strong lensing data and spectroscopic measurements of stellar dynamics in the central galaxy of three clusters which contain both radial and tangential arcs to find an average value $\alpha = 0.52 \pm 0.05$, but they also find evidence for a significant scatter

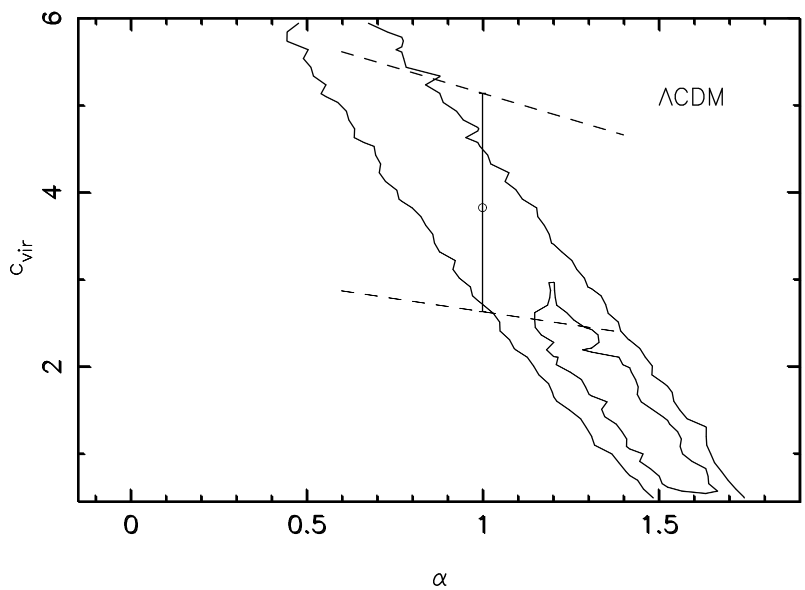

Figure 1: The contours show the 68% and 95% confidence intervals for the concentration $c_{\rm vir}$ and inner slope α of our average cluster halo. Also shown is the mean value and scatter in $c_{\rm vir}$ for an NFW halo of similar mass, predicted by Bullock et al. (2001). The dashed lines indicate lines along which the two parameters are degenerate. See also Dahle et al. (2003).

$\Delta\alpha \sim 0.3$. On the other hand, Bautz & Arabadjis (2003) find $1 < \alpha < 2$ and Lewis, Buote & Stocke (2003) find $\alpha = 1.19 \pm 0.04$, based on *Chandra* observations of the X-ray luminous intracluster medium in four clusters and in one cluster, respectively. In contrast to our weak lensing study (which only probe the DM density profile at radii where the baryonic component is not dynamically dominant), these strong lensing and X-ray studies are not directly comparable to simulations that only contain collisionless CDM. The above results indicate that future observational studies should simultaneously take into account both the baryonic component in stars and in the X-ray luminous intracluster medium as well as the DM. Similarly, all these components must be properly modeled in numerical simulations, if the simulations are to be directly compared to cluster observations on small (≤ 10 kpc) scales. In any case, all the recent studies indicate that the core sizes of massive clusters are too small to be consistent with any self-interacting dark matter having a cross section large enough to explain the rotation curves of dwarf galaxies.

Like previous weak lensing studies (e.g., Clowe & Schneider 2001, Hoekstra et al. 2002), we are not able to strongly distinguish between the outer slope of an isothermal sphere, $\rho \propto r^{-2}$, and the NFW slope $\rho \propto r^{-3}$. However, in a recent work, Kneib et al. (2003) use a combination of weak and strong gravitational lensing data based on HST imaging of the cluster CL0024+17 to find an outer slope > 2.4. Their data is adequately fit by a NFW profile with $c = 22^{+9}_{-5}$, significantly higher than typical observed concentration parameters of rich clusters (e.g., Hoekstra et al. 2002; Katgert, Biviano & Mazure 2003), which are generally consistent with CDM predictions (see also Fig. 1). However, *Chandra* X-ray data (Ota et al. 2003), as well as dynamical studies based on galaxy spectroscopy (Czoske et al. 2002), indicate that this is not a fully relaxed, spherically symmetric system. Weak lensing measurements of a representative sample of dynamically relaxed clusters out to even larger radii than we probe in our study should eventually settle the issue of the value of the outer slope.

Acknowledgments

I thank my collaborators Steen Hannestad and Jesper Sommer-Larsen, and acknowledge support from The Reseach Council of Norway through a post-doctoral research fellowship.

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